TFAWS Active Thermal Paper Session

Laser Processed Condensing Heat Exchanger (LP-CHX) Test Article Design, Manufacturing, and Testing

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Outline

- Problem Statement
- Technology Overview
- Design & Fabrication
- Testing
- Results
  - Microbial Growth
  - Water Quality
  - Heat Transfer
- Future Plans

Problem Statement & Technology Overview

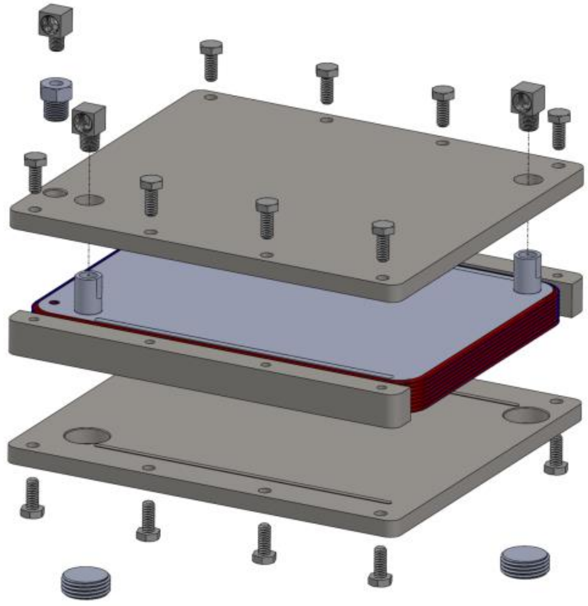
CHX Problem Statement

- CHX are a critical function of closed-loop life support
  - Provide sensible and latent cooling to the vehicle
  - ~50% of reclaimed water on ISS is from CHX condensate
- Current technology utilizes a hydrophilic coating to gather condensate and control microbial growth in conjunction with a monthly dry-out. Slurper bars and water separator is used to draw condensate off the CHX, delivering it to the WPA
- Three problems with current technology
  - Coating longevity
    - *Hydrophobic contamination* turns hydrophilic surfaces hydrophobic leading to *water carry-over*
    - *CHX's must be uninstalled and refurbished* on a regular basis (significant crew time & resources)
  - Microbial and fungal growth concerns
    - Current coating utilizes silver oxide to mitigate microbe growth and *must be dried out on a monthly basis* to prevent bio-film formation
    - Potential for flaking, potential for hydrophobic contamination, and additional logistics tracking with MCC
  - Current coatings may react with airborne contaminants which may cause downstream impacts to WPA
    - *Chemical reaction between contaminants and coatings* which produce DMSD's that degrade filters in the WPA
    - Currently on ISS, WPA filters can remove compounds, but are degraded at an accelerated rate (replaced every year)

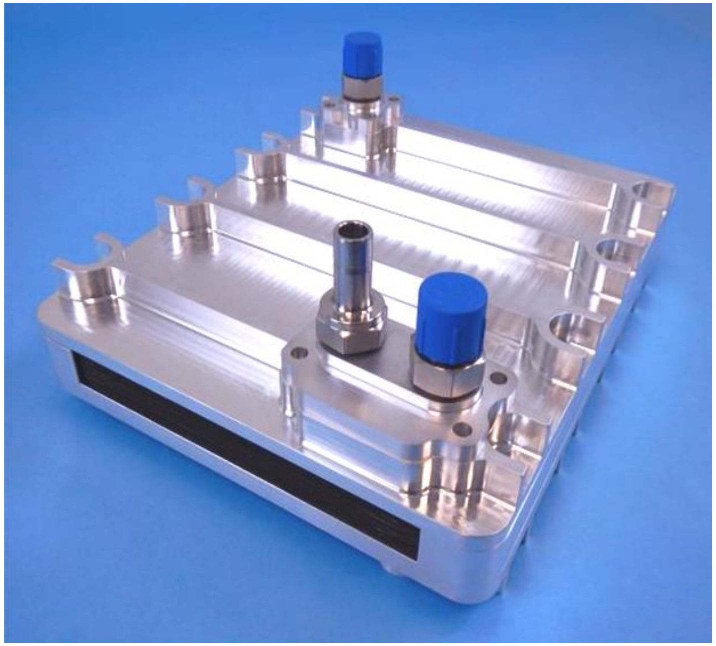
To enable long duration spaceflight and reduce upmass/downmass a more robust CHX is needed

LP-CHX Technology Overview

- Dimpled plate heat exchanger replaces typical plate/fin heat exchanger
- Condensing surfaces are 99.95% pure laser processed silver
  - Laser processing allows for increased surface area and silver ion production (i.e. antimicrobial condensing surface)
- Designed to “eject” condensate from the outlet of the LP-CHX
- Active or passive water separator is implemented directly downstream of the LP-CHX and sized for full airflow (400 CFM), condensing rates (~3.2 lbs/hr), and various water droplet dimensions (functions similar to current water separator)
  - COSMIC is being developed by Paragon
  - Alternatively, the Water Capture Device (WCD) being developed by Sierra Nevada could be implemented with the LP-CHX



Exploded View of LP-CHX



LP-CHX Scale Test Article

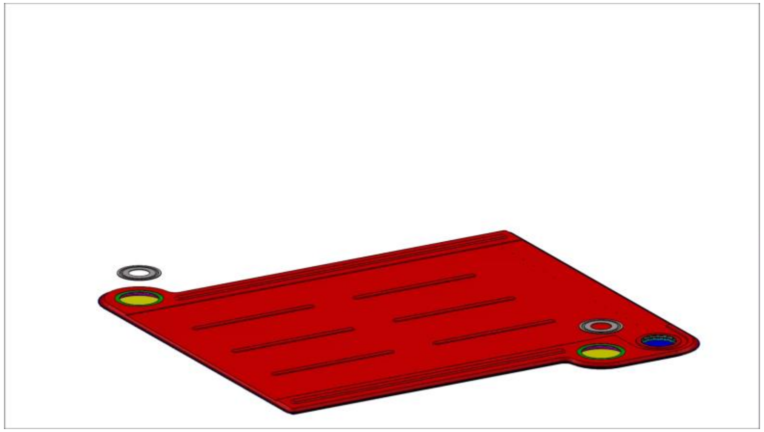
Design & Fabrication

Manufacturing & Testing Team

Design & Assembly → ***Laser Processing*** → ***Testing***

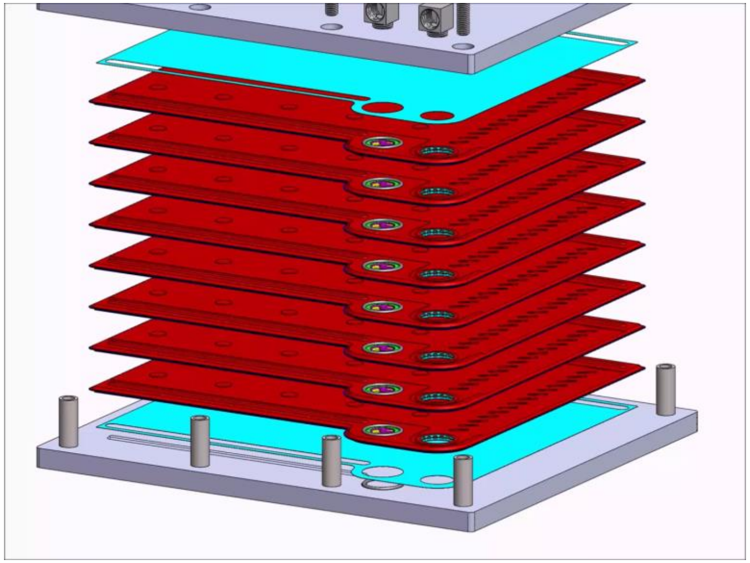
LP-CHX Manufacturing

- Significant development effort led by Edare/Creare/UNL team to establish manufacturing methods for the LP-CHX
  - Design utilizes a stainless steel packet enveloped by a silver, laser processed packet
  - Packets stacked (modular design), laser welded together, then encased in outer support structure (manifold)
  - Air and condensate only interact with silver laser processed surfaces
  - Coolant only interacts with stainless steel
- Concept is a line-of-sight design for ISS flight demo with opportunities to significantly decrease manufacturing complexities and weight if selected
  - Stainless/silver packet enveloping design can be eliminated if silver can be deposited onto stainless steel sheets then laser processed
- Test article was comprised of 8 packets, full scale unit would utilize 142 packets



Packet Assembly Video

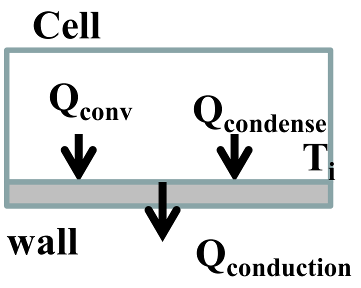
Packet Assembly Video



LP-CHX Assembly Video

Thermal Analysis approach

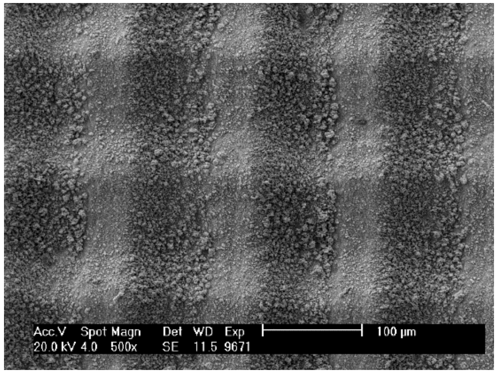
- Air side pressure drop
  - Assume laminar flow in a rectangular channel
  - Keep this number below the 1 in. H_2O limit to leave room for additional pressure drops entering the HX
- Liquid side pressure drop
  - Series of DP calculations based on geometry and local liquid velocity
  - Most of the pressure drop is in the various manifolds. The final design will accommodate the required pressure drop
- Air side heat transfer and condensation
  - Gas and water layers are in counter-flow
  - Convective heat transfer from bulk gas flow to the walls: Use Nusselt number based on laminar flow and constant wall temperature (Nu = 3.657)
  - Condensation of vapor onto the wall: Used air-water diffusion coefficient and heat/mass transfer analogy (Sh = Nu for laminar flow) to estimate the mass transfer coefficient
  - Conduction out of the gas channel: Thermal resistance modeled for walls and flowing coolant
  - To compare with demo data, we built heat leak into the model by using the measured coolant inlet and outlet temperatures
- To run the model
  - Model was run in excel and validated against the demo unit data
  - Stepped through the HX in 1 inch steps
  - At each cell, determine the interface temperature (T_i) by ensuring a heat transfer balance between convection, condensation and conduction
  - Determine the gas bulk temperature in the next cell based on an enthalpy balance



Laser Processing of Silver

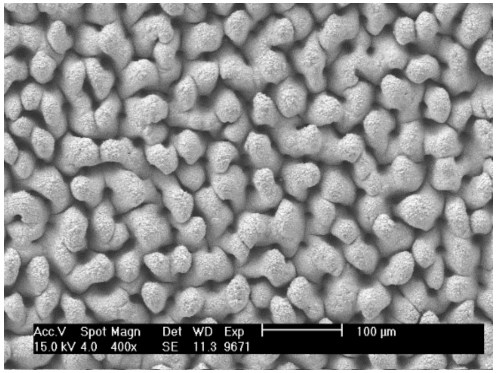
- Femtosecond Laser Surface Processing (FLSP) completed at University of Nebraska-Lincoln
- Several methods of laser processing attempted including direct writing, dual pulse, low energy FLSP
- SEM images and 3D surface analysis with a laser scanning confocal microscope to:
  - Confirm structure formation on silver surfaces
  - Ensure laser processing does not "punch" holes into silver substrate (substrate is 0.006" thick)
  - Verification of consistency between plates processed

Direct Writing



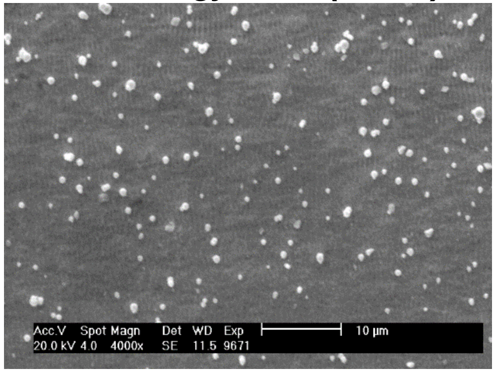
Caused warping of silver substrate

Dual Pulse FLSP



Utilized this method of processing for all test articles

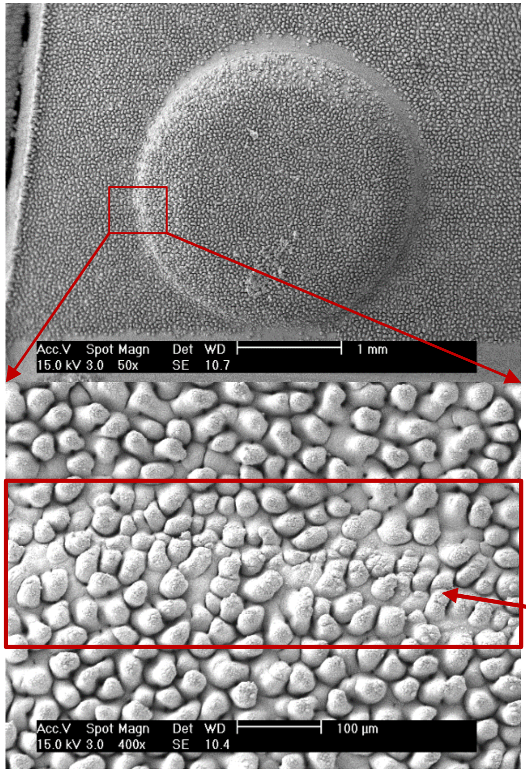
Low Energy FLSP (LIPSS)



Did not improve anti-microbial properties

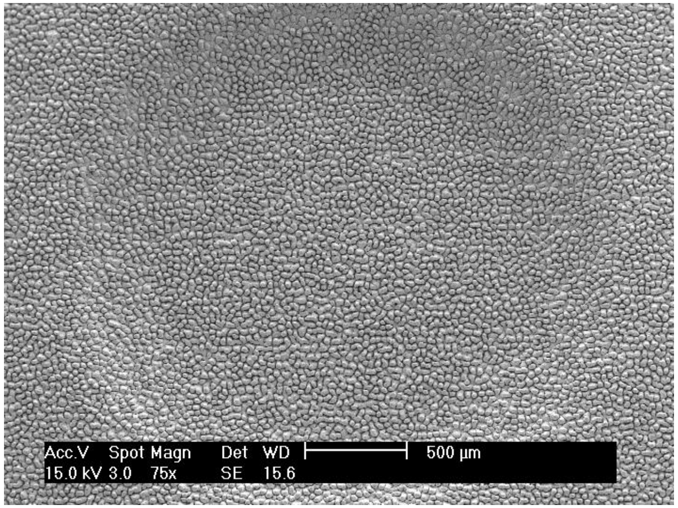
Laser Processing Dimples (1/2)

- For dimpled LP-CHX, methods were developed for processing dimples and confirmed with SEM
- Utilized a lens with a long focal length in order to minimize the difference in fluence and shot number as the height changes across the surface



Transition from dimple to flat area

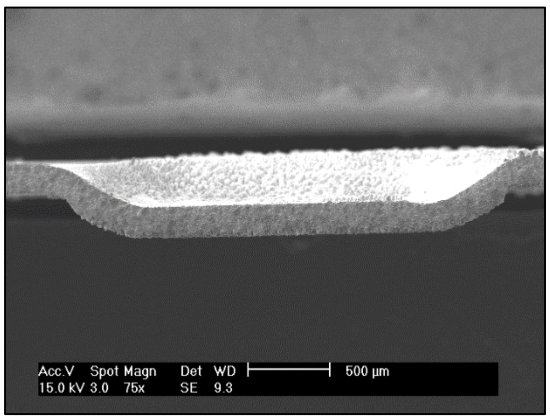
Positive Side of Dimple SEM Images

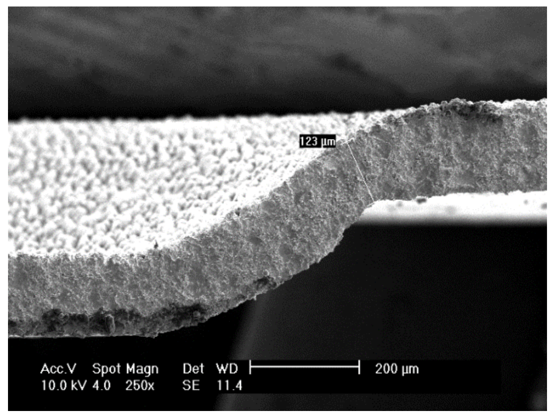


Negative Side of Dimple SEM Images

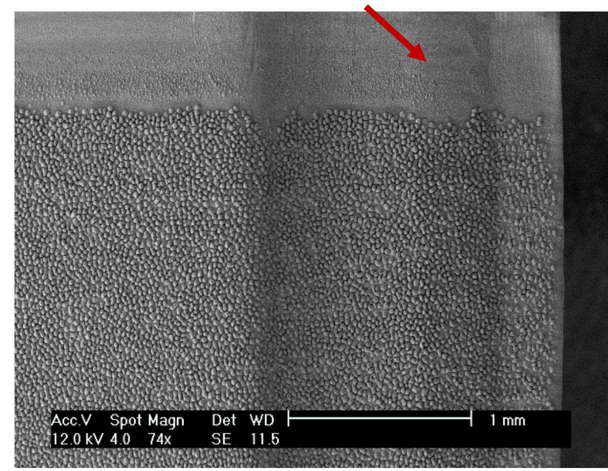
Laser Processing Dimples (2/2)

- Ensured processing of dimple did not introduce pin-holes into dimpled area
  - Also ensured forming of dimples did not tear silver at stress areas
- Ensured processing over laser welds could be completed successfully





Weld Bead



SEM images of slide across dimpled area (thinnest part) of the sample is ~65 µm (.0026") along the outer contour of the dimple

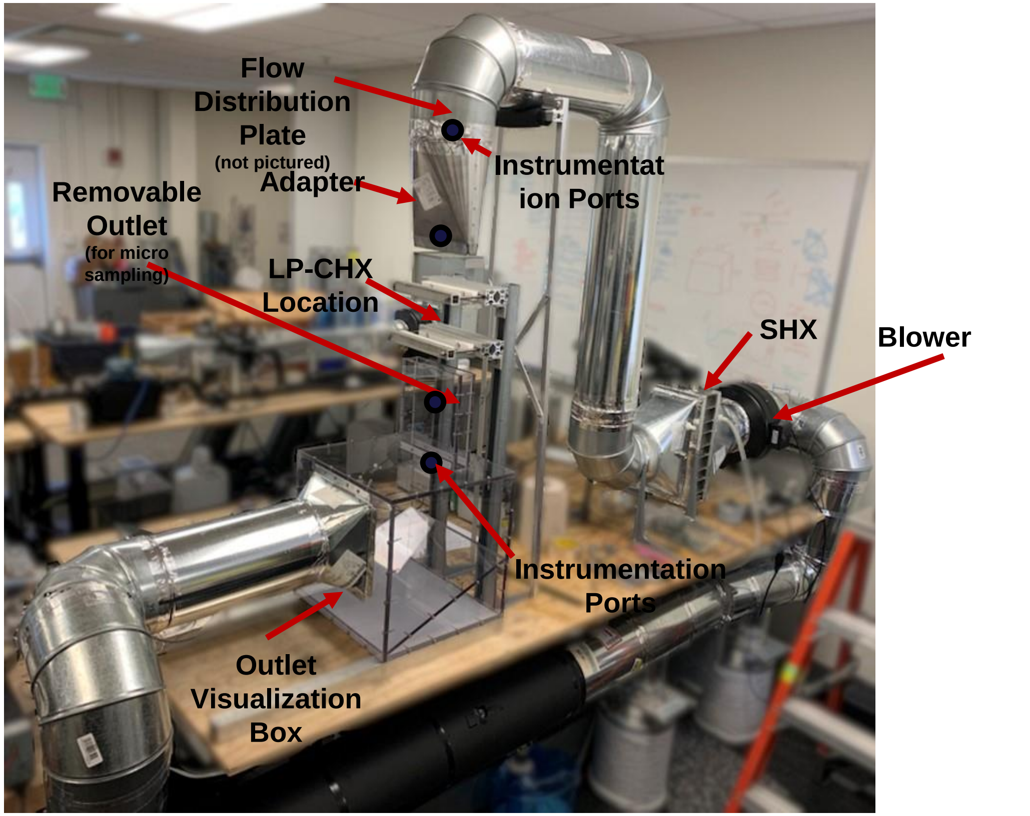
Testing

LP-CHX Long Duration Testing

Scaled test article delivered to JSC for long duration testing (6-months)

<u>Test Objectives</u>

- *Micro/Fungal Growth*: Determine efficacy of FLSP silver condensing surfaces on micro/fungal growth during test duration (i.e. microbial/fungal growth resistance)
- *Water Quality:* Determine water quality over time (specifically silver ion concentrations)
- *Heat Transfer:* Determine sensible/latent heat transfer rates and pressure drop vs. flow rate to size a full scale unit



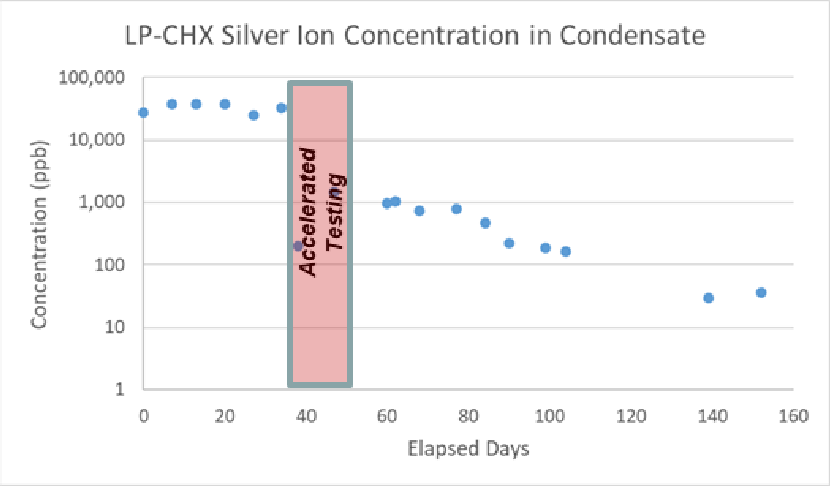
LP-CHX Test Stand

Results

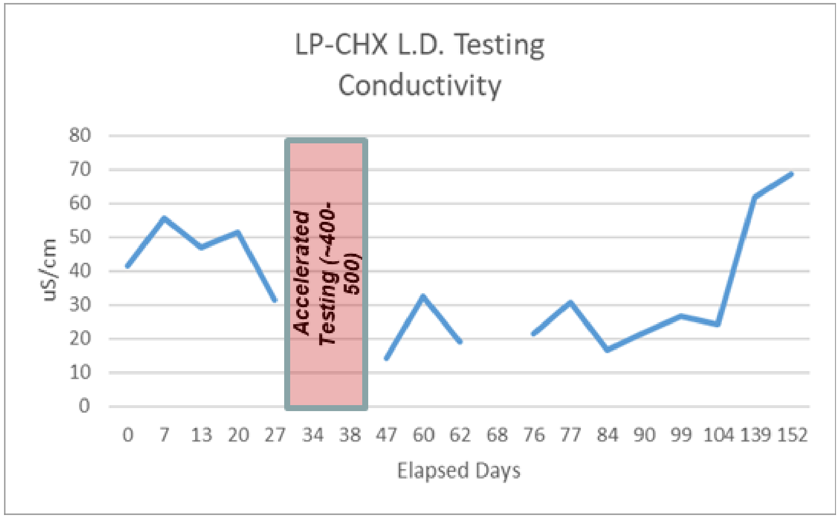
Water Quality

Criteria Summary: Prevent or reduce introduction of contaminants into condensate water over the lifespan of the CHX
Goal: Condensing surfaces are to be chemically inert, compatible with the ISS Water Processor and downstream components, and 5 years life without degradation of performance
Threshold: Condensing surfaces are to be chemically inert, compatible with the ISS Water Processor and downstream components, and 3 years life without degradation of performance

- Long duration testing indicates condensate water quality is acceptable to WPA (per Layne Carter) with the exception of significantly high silver ion concentrations at test start
- As a result, LP-CHX must undergo initial "condensing flush" before delivery for flight
- *Criteria Summary:* Based on water quality samples from testing, the LP-CHX meets performance goal but will require an initial condensing flush



LP-CHX Condensing Surface



Microbial Growth

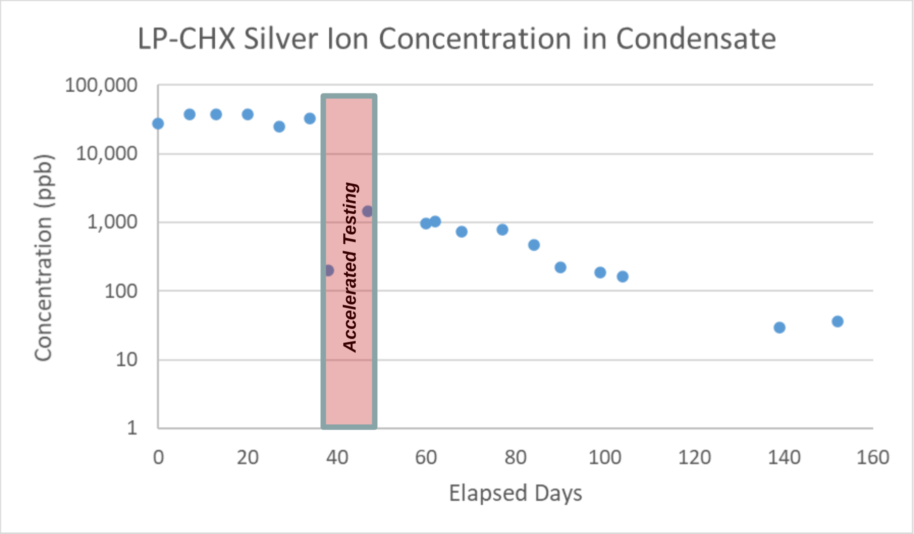
- Weekly micro and fungal samples taken from LP-CHX test article
- Loop was inoculated via aerosol spray every other week
  - 10^4 bacteria
  - 10^3 fungi
- Microbial consortium used in this study
  - Bacillus megaterium
  - Staphylococcus epidermidis
  - Sphingomonas paucimobilis
  - Aspergillus niger
- Conclusions: Low levels of microbes were recovered indicating a high level of microbial control provided by the laser processed surfaces

Date	Elapsed Days	Bacterial cfu/mL	Fungal cfu/mL	Microorganism
9/12/19	0	0	0	N/A
9/24/19	12	0	0	N/A
10/8/19	26	0	< 1	*A. niger*
10/22/19	40	0	< 1	*A. niger*
Accelerated Testing (10/24-29/2019)				
11/4/19	53	0	0	N/A
11/12/19	61	< 1	< 1	*Sphingomonas* species, *Penicillum chrysogenum*
11/26/19	75	2	3	*Paenibacillus tundrae*, *B. megaterium*, *Microbacterium oleivorans*, *Bacillus* species, *A. niger*
12/10/19	89	< 1	2	*M. oleivorans*, *Bacillus* species, *A. niger*
12/31/19	110	54	1	*Methylobacterium goesingens*, *Sphingomonas* species, *Sphingomonas ginsenosidimutans*, *Burkholderia* species, *A. niger*
1/16/20	126	< 1	< 1	*Sphingomonas* species, *A. niger*
2/4/20	145	18	< 1	*Sphingomonas adhaesiva*, *Sphingomonas* species, *P. tundra*, *P. chrysogenum*, *A. niger*
2/18/20	159	44	< 1	*P. tundrae*, *B. megaterium*, *Sphingomonas* speices, *Microbacterium* species, *Sphingomonas desiccabilis*, *A. niger*
3/5/20	175	25	< 1	*Sphingomonas* speices, *Microbacterium* species, *Methylobacterium* species, *A. niger*

Microbial Growth Continued

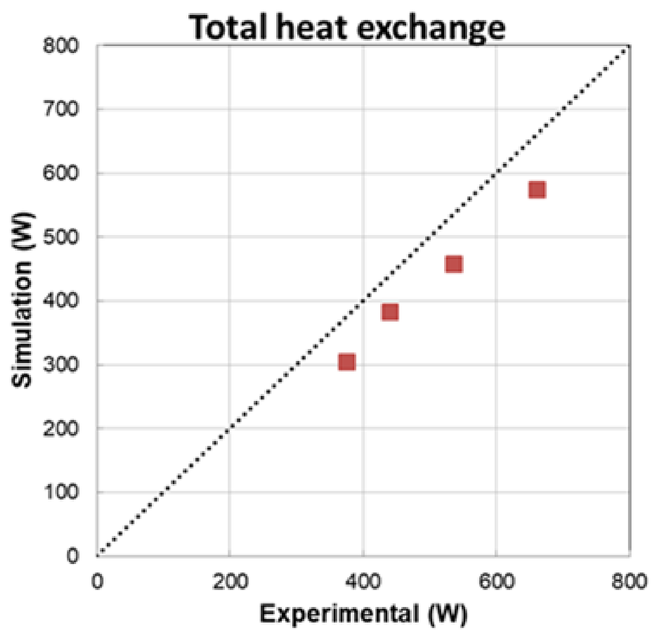
Criteria Summary: Prevent or mitigate formation of microbial growth and bio-film
Goal: Operational surface and water cleanliness: 1,000 cfu/ml; Ability to prevent inhibit biofilm formation (visual and/or microscopic analysis); Method to remediate the system (if needed)
Threshold: Operational surface and water cleanliness: 10,000 cfu/ml; Ability to prevent inhibit biofilm formation (visual and/or microscopic analysis); Method to remediate the system (if needed)

- *Criteria Summary:* For current testing durations of the LP-CHX test article, the laser processed surfaces utilized in the test article offer microbial growth control, meeting performance goal.



Heat Transfer

- Comparison of the heat transfer model to the resultant data shows that the model over-predicted performance
- Originally, the model predicted 91 packets needed to meet a full sized heat load. Future plans increase the number to 142 packets



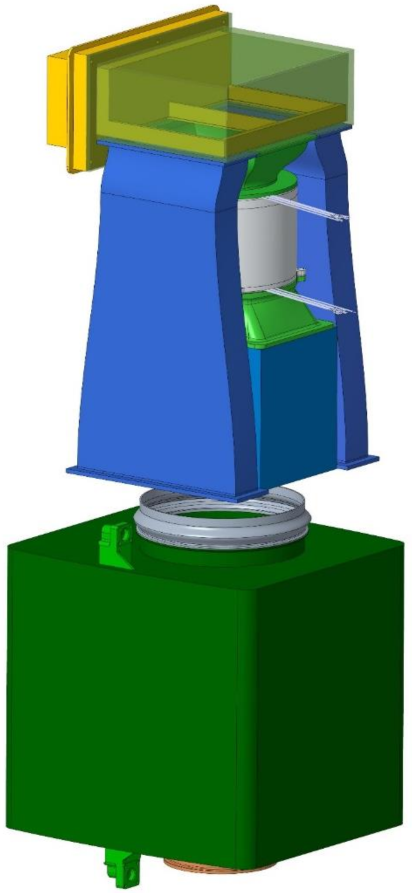
Operating parameters for the plotted points

Parameter	units	1_7_ Part 1	1_31_ Part 1	1_15_ Part 5	1_13_ Part 7
Tair_in	(C)	25.47	25.49	25.09	25.6
Dewpoint	(C)	13.61	17.22	20.48	24.36
T_cool_in	(C)	4.04	4.01	4	4.04
T_cool_out	(C)	11.63	12.26	13.37	14.53
Fan Speed	(ft/min)	1004	1049	1087	1082
coolant flow rate	(pph)	100	100	100	100

Conclusions & Future Plans

Conclusions

- A successful scaled LP-CHX test article was designed, manufactured, and tested for 6 months
- During 6 month testing, the LP-CHX provided valuable insight into water quality, microbial growth, and heat transfer
  - Water quality met requirements for downstream components, in particular the WPA
  - For current testing durations of the LP-CHX test article, the laser processed surfaces utilized in the test article offer microbial growth control, meeting performance goal.
  - Heat transfer was slightly under predicted by the model created, resulting in more packets needed in a full scaled unit (142 vs. 91 originally)
- Conclusions & Future Plans
  - Investigation of electroplating directly to silver to significantly decrease manufacturing complexities, costs, and schedule
  - Full-scale LP-CHX manufacturing and testing with electroplated concept
  - Ultimately, an ISS demo with integrated water separator



Rear view of LP-CHX/COSMIC ORU & Inlet ORU (Green Box)

Thank You!!!

- Edare
  - John Sanders
  - Dr. Mike Izenson
- UNL
  - Dr. Dennis Alexander
  - Dr. Craig Zuhlke
  - Nick Roth
  - Aaron Ediger
- NASA
  - Dr. Sarah Wallace
  - Tanner Hamilton
- NASA Interns
  - Riley Daulton
  - Dan Deveney
  - Thomas Gross
  - Alexandra Alaniz
  - Naina Noorani

FEA Analysis

Finite Element Analysis (FEA) Background

FEA evaluation of sandwich response to internal water pressure

Geometry is a corner of the full stack

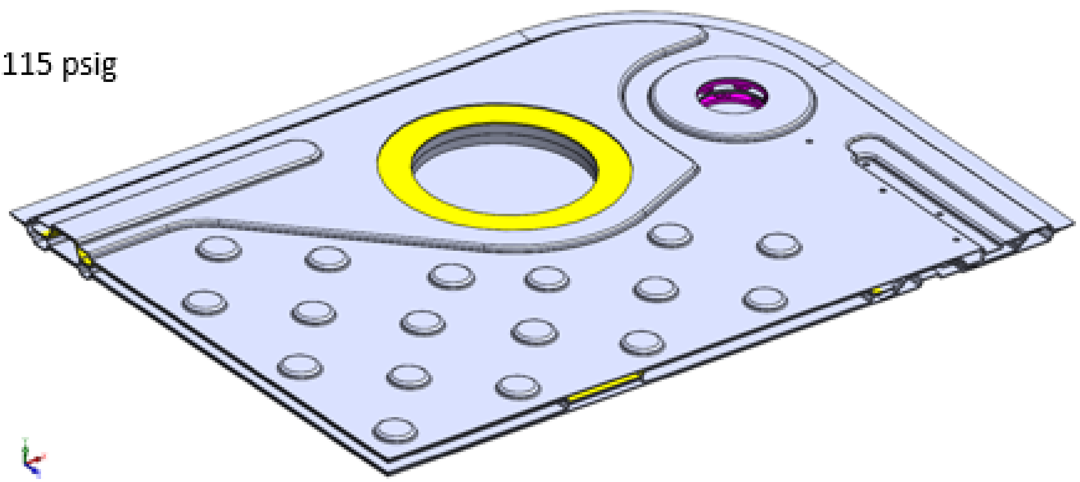
Includes all critical features

Checked four conditions:

1. Preload compression by endplates (semi-arbitrarily 0.1 mil per sandwich)
2. Maximum Design Pressure (MDP) = 115 psig
3. Proof = 1.5*MDP = 172.5 psig
4. Burst = 3.5*MDP = 402.5 psig

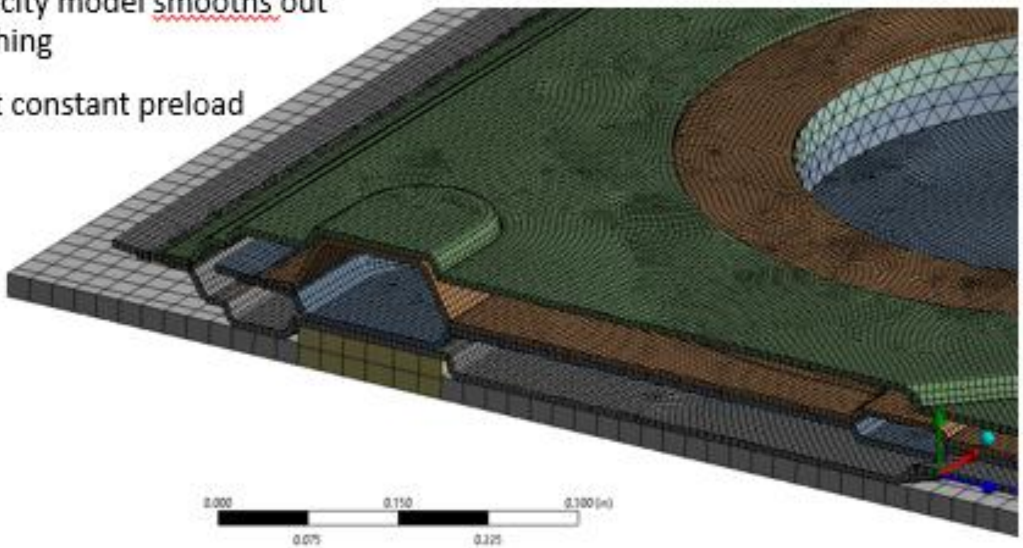
Material models:

- 316L, Chaboche plasticity
- Silver, linear elastic
- TIM, approximated linear elastic



FEA Setup

- Top and bottom endplates provide compressive boundary condition
    - For clarity, only one shown at right
- Mesh resolution captures most behaviors we care about
    - Especially in stainless parts, plasticity model smooths out numerical inaccuracies from meshing
- Load steps increase internal pressure at constant preload



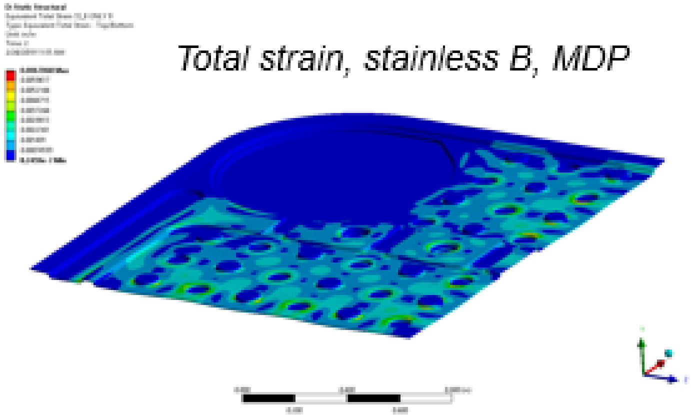
FEA Failure Criteria and Results Summary

- Stainless
  - ✓ MDP, no accumulation of significant plastic strain from a non-reversing fatigue load
  - ✓ Proof, total strain << ultimate strain
  - ✓ Burst, total strain < ultimate strain
- Silver
  - ✓ MDP, no accumulation of significant plastic strain from a non-reversing fatigue load
  - ✓ Proof, N/A because won't be part of the proof test
  - ✓ Burst, N/A because won't be part of the burst test

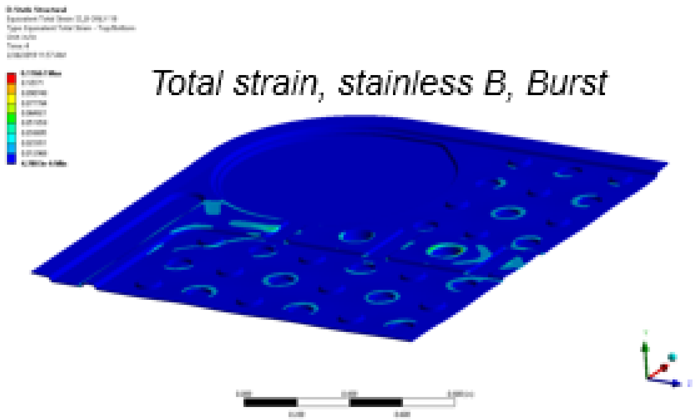
Total Strain	Stainless	Silver
Load Step	%	%
Preload	0.04	0.1
MDP	0.7	1.0
Proof	1.2	1.4
Burst	12	3.2
Typical yield	0.2	0.2
Typical ultimate	50	~2-8 (after ~30% cold work, ~ full hard)

FEA Results, Stainless

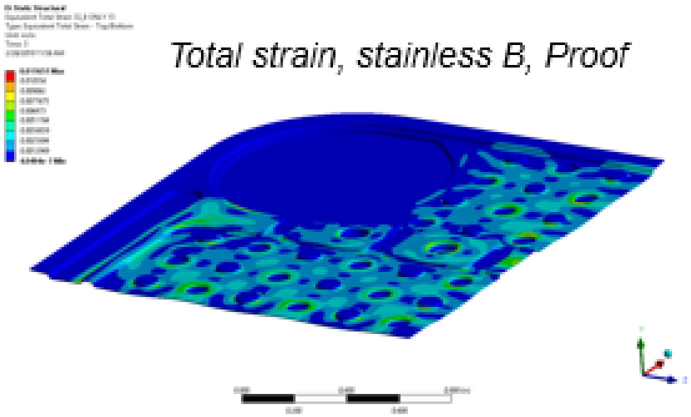
- Max. strain << ultimate strain, especially near welds
  - Note color scale varies by load step
- Modest plastic strain at MDP will result in a checkerboard pattern that won't accumulate strain without a reversing load
- At burst, max. strain is at dimples as they're crushed
  - Not a likely leak risk



Total strain, stainless B, MDP



Total strain, stainless B, Burst

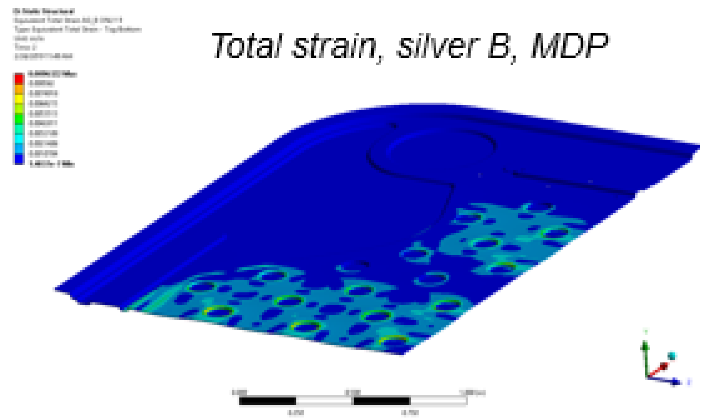


Total strain, stainless B, Proof

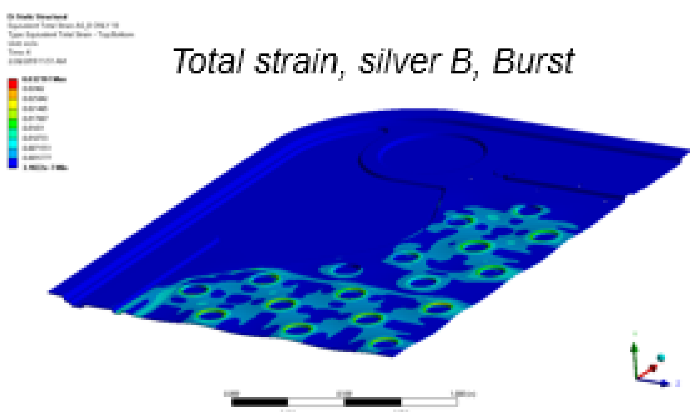
FEA Results, Silver

- Max. strain occurs far from welds
  - Note color scale varies by load step
- Modest plastic strain at MDP will result in a checkerboard pattern that won't accumulate strain without a reversing load
- Plastic strains at Proof and Burst are still modest
  - Would not be subjected to these conditions, but it is instructive to see what would happen

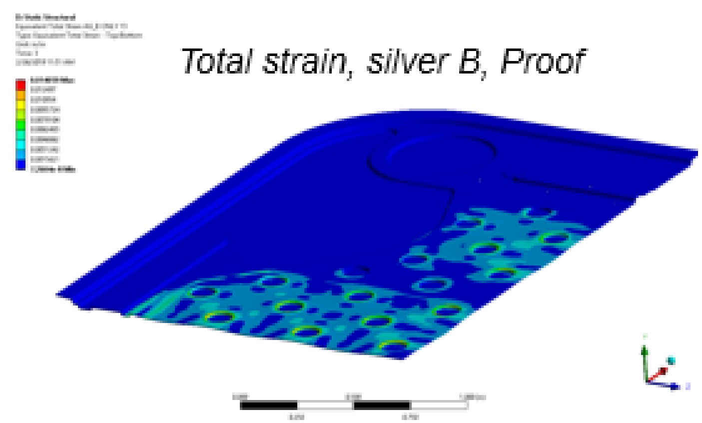
Total strain, silver B, MDP



Total strain, silver B, Burst

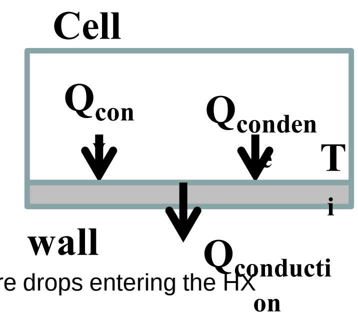


Total strain, silver B, Proof



Thermal Sizing

Analysis approach



- Air side pressure drop
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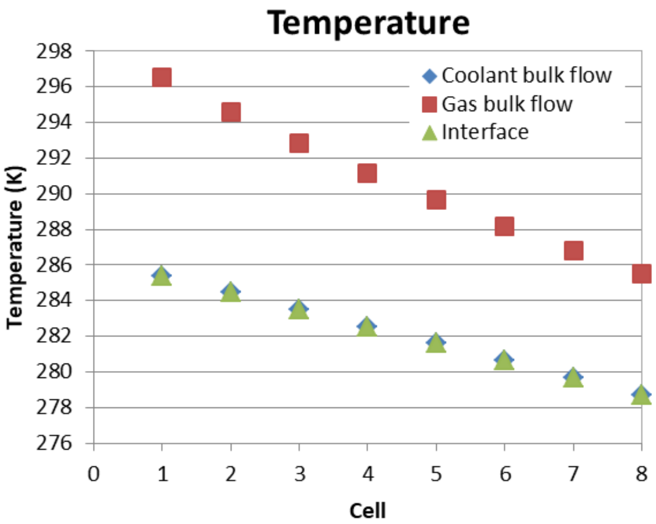
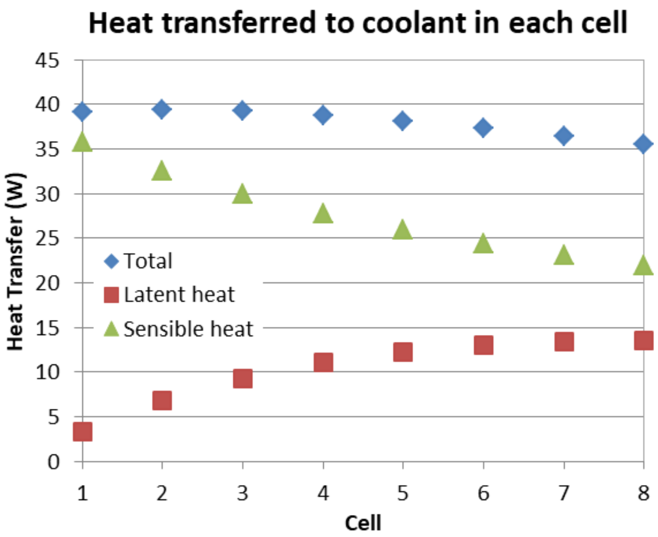
Example calculation for the demo unit





Full scale design

Key design parameters selected to achieve goals for heat transfer, condensation, and pressure drop:

- Number of layers: 142
- Air channel height: 0.042 in.

Predicted performance

- Sensible heat transfer: 2.5 kW
- Latent heat transfer: 1.0 kW
- Condensation rate: 0.41 g/s = 3.2 lb_m/hr
- Gas side pressure drop: 0.87 in. H_2O
- Liquid side pressure drop: 1 psi (approximate, will fine tune in the final design)
- Core height: 14.2 in.

Air exit conditions: 8° C (46° F) and 91% RH

Full scale design operating conditions

Coolant flow	1230	lb_m/hr
Inlet air pressure	14.97	Psia
Inlet air temperature	72.6	°F
Inlet coolant temp	40	°F
Air flow	276	ft^3/min
Inlet dew point	54.8	°F
Sensible heat exchange	2500	W
Condensate	3.2	lb_m/hr